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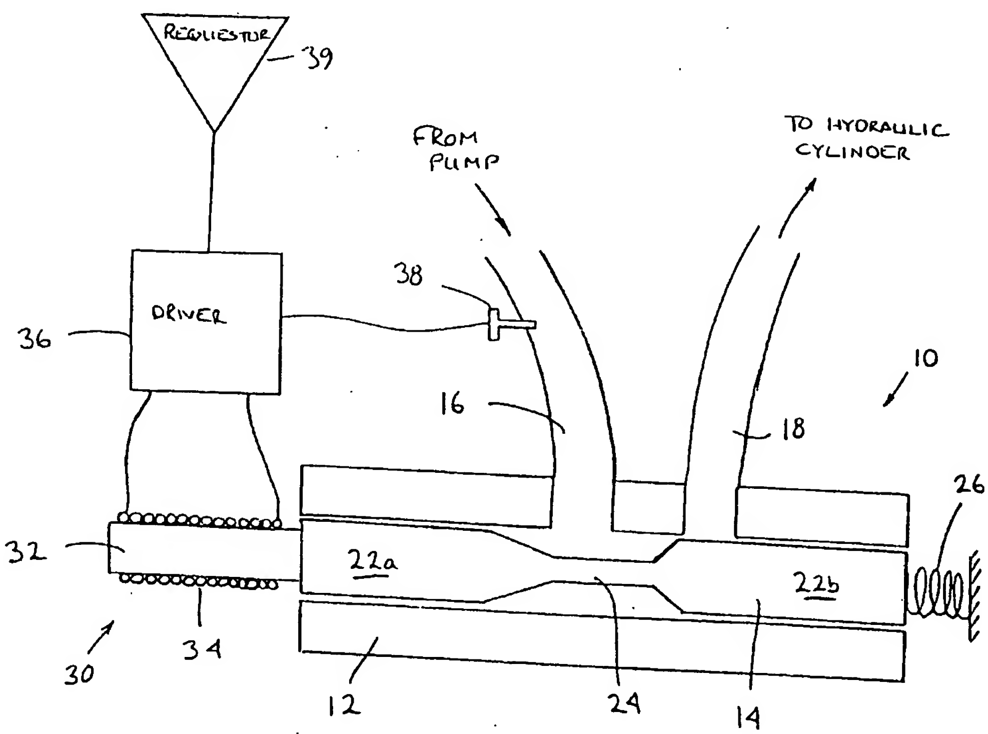
(54) **MECANISME D'ENTRAINEMENT D'UNE VANNE MAGNETIQUE A COMMANDE ELECTRIQUE AVEC COMPENSATION POUR LES CHANGEMENTS DANS LA RESISTANCE DE LA BOBINE**

(54) **AN ELECTRICALLY CONTROLLED SOLENOID VALVE DRIVER WITH COMPENSATION FOR COIL RESISTANCE CHANGES**



(57) To precisely control an electrically controlled solenoid valve, the resistance of the solenoid coil is measured either indirectly through measuring the temperature of the coil or directly by placing a known resistance in series with the solenoid or applying a known current source to the solenoid. Based on the measured coil resistance, the voltage applied to the coil is adjusted so that a desired current through the coil is achieved.

ABSTRACT

To precisely control an electrically controlled solenoid valve, the resistance of the solenoid coil is measured either indirectly through measuring the temperature of the coil or directly by placing a known resistance in series with the solenoid or applying a known current source to the solenoid. Based on the measured coil resistance, the voltage applied to the coil is adjusted so that a desired current through the coil is achieved.

AN ELECTRICALLY CONTROLLED SOLENOID VALVE DRIVER WITH COMPENSATION FOR COIL RESISTANCE CHANGES

BACKGROUND OF THE INVENTION

This invention relates to a solenoid valve driver and a method of controlling solenoid valves.

Many machines have parts which are moved by hydraulic or pneumatic cylinders. Such machines use valves to control the cylinders. These valves are often electrically operated. Where a machine operator has a joystick to control each electrical valve, the valves are generally bang-bang (i.e. on-off) or proportional solenoid valves. Solenoid valves are not known for a high degree of accuracy, but they are inexpensive and function satisfactorily in many applications. On the other hand, the inaccuracy of such valves can be problematic where machines operated by the valves either move in envelopes having small tolerances or employ closed loop control schemes. For example, imprecise valve control may be satisfactory for a machine with a boom moved by three cylinders where there is an equal number of joysticks such that one joystick controls the valve to each of these cylinders. On the other hand, such imprecision is generally not tolerable where the same boom is moved in three dimensions by a single joystick though a closed loop control scheme.

For precise control of a solenoid valve, a current source has been used to drive the solenoid. Another approach has been to utilize a control system which feeds back actual valve position. A further known option is to dispense with a solenoid valve in favour

of a servo controlled valve. However, all of these options are relatively expensive, especially when a machine has a great number of control valve drivers.

This invention seeks to overcome drawbacks of prior solenoid valve drivers.

SUMMARY OF INVENTION

According to the present invention, there is provided a method of controlling a solenoid valve comprising the steps of: applying a control voltage to said valve; measuring resistance of a solenoid coil of said solenoid valve; adjusting said control voltage based on said measured resistance.

According to another aspect of the present invention, there is provided a driver for an electrically controlled solenoid valve, comprising: a temperature sensor for measuring a temperature of a solenoid coil of said solenoid valve; a compensator responsive to said temperature sensor for adjusting a voltage supply providing a voltage across said coil.

BRIEF DESCRIPTION OF THE DRAWINGS

In the figures which illustrate preferred embodiments of the invention,

figure 1 is a schematic view of a machine incorporating a solenoid valve made in accordance with this invention,

figure 2 is a schematic view of a solenoid valve with a driver made in accordance with this invention,

figure 3 is a schematic view of one embodiment for the driver of figure 2, and

figure 4 is a schematic view of an alternate embodiment for the driver of figure 2.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Turning to figure 1, a machine 100 has a boom 102 which is manipulated by hydraulic cylinders 104. Each cylinder is input with working fluid from a solenoid valve 10 associated with a valve manifold 106.

Turning to figure 2, each solenoid valve 10 comprises a valve body 12 and a valve spool 14. An oil inlet 16 and an oil outlet 18 extend through the valve body. The inlet receives oil from an oil pump and the outlet outputs oil to an hydraulic cylinder.

The valve spool has large diameter ends 22a, 22b and a narrow medial portion 24. The valve is biased to a closed position by spring 26 whereat the large diameter ends seal against the valve body.

A solenoid 30 has a solenoid core 32 which abuts end 22a of the valve spool and a coil 34. The coil is electrically connected to a driver 36. A temperature sensor 38 is inserted in the oil inlet 16 and is electrically connected to the driver. A requestor 39 is also electrically connected to the driver.

The driver 36 is detailed in figure 3. Turning to figure 3, the driver comprises a supply voltage source 40 which provides a voltage, V_{bat}, a pulse width modulator (PWM) 42 which comprises a controlled switch 44, and a controller 46. The temperature sensor 38 and requestor 39 are electrically connected to the controller of the driver. The controller has an internal clock 48 which has a clock period. The controller outputs to the PWM on control line 50 and senses voltage across the solenoid on sensing line 52. In figure 3, the solenoid is modelled as a resistor 130 which represents the coil resistance, R_c.

Referencing figures 2 and 3, in overview of the operation of the driver, a request to open the valve a precise amount may be received by the controller 46 from the

requestor 39. (The requestor may comprise, for example, the output from a control algorithm for a joystick.) In response to this request and an input from temperature sensor 38, the controller selects a portion of each clock period (the "duty cycle") during which voltage should be applied to the solenoid coil. Based on this selection, the controller sends commands to the PWM so that the PWM closes its switch 44 during the selected portion of each period. The controller measures the voltage applied to the solenoid by monitoring voltage on sensing line 52.

The force on the solenoid core 32 is a function of the average current flowing in the coil 34. The average current is directly proportional to the average voltage applied across the solenoid, and the average voltage is dependent upon the duty cycle. As the force on the solenoid core increases, the solenoid core forces the valve spool 14 to open to a greater and greater extent against the force of spring 26.

The subject invention recognises that the resistance of the coil, R_c, is a variable. Since the average current flowing in the coil 34 is inversely proportional to the actual resistance of the coil, R_c, it is therefore important to be able to determine the actual value of this resistance in order to precisely control valve 10. It is recognised that the variability of the coil resistance is primarily a function of temperature changes. Temperature sensor 38 is inserted in the oil inlet 16 of valve 10. The temperature of the valve will approximate that of the oil which flows through it. This temperature will also be conducted to the solenoid 30 such that the temperature measured by sensor 38 is a good approximation of the temperature of solenoid 30 and this temperature forms an input to controller 46. The controller uses the temperature information to adjust the average voltage so that the average current flowing through the solenoid is at a desired level.

The controller may adjust the average voltage in several different ways.

Firstly, given that:

t_{on} is the time the waveform is at the supply voltage, V_{bat} (the rest of the time the waveform is typically at ground or 0 Volts or -0.7 Volts if a flyback diode is being used)

and

T is the period of the clock

then

$n = t_{on} / T$ where n is the amount of time in each period the supply voltage is connected, thus, n is the "duty cycle"

and

$V_o = n * V_{bat}$ where V_o is the nominal average output voltage

Based on the temperature indication from sensor 38, the controller may access a look-up table to look up the coil resistance, R_{new}, for that temperature. Then, assuming the desired current through the solenoid is $i_{desired}$ and that this current is achieved using V_o when the solenoid is at 25°C -- at which temperature the resistance of the coil is $R_{nominal}$, to maintain current constant as coil resistance changes to R_{new}, the average

output voltage is adjusted to match the change in resistance, i.e.:

$$v_{actual} = V_o * (R_{new}/R_{nominal}) \quad \ldots\ldots 1$$

then

$$i_{actual} = v_{actual} / R_{new} = [V_o * R_{new} / R_{nominal}] / R_{new} = V_o / R_{nominal} \approx i_{desired} \quad \ldots\ldots 2$$

Therefore, to compensate for the change in solenoid resistance, the controller multiplies the nominal output voltage, V_o, by the correction factor (R_{new} / $R_{nominal}$) to obtain the desired output current, $i_{desired}$.

Instead of looking up R_{new}, based on the temperature, the controller could access a look-up table containing voltage correction factors as a function of temperature. Then:

$v_{actual} = V_o * k$ where k is a correction factor

While the temperature sensor 38 has been shown as inserted into the oil inlet, it may equally be inserted into the oil outlet or valve body. Further, a machine often has a considerable number of hydraulic cylinders, each with a controlling valve. In such instance, the valves are normally attached to a common valve manifold as is depicted for machine 100 of figure 1. With this configuration, a single temperature sensor may be inserted in the manifold and the temperature reading used by the controller for each solenoid valve as representative of the temperature of the solenoid.

Figure 4 illustrates an alternate driver. Turning to figure 4 where like parts have been given like reference numerals, a controlled switch 56 having switches 56a and 56b and a reference resistor 58, $R_{reference}$, are connected in series with the solenoid coil resistance 130. The reference resistor is fabricated of a temperature insensitive material. Controller 146 has a control output 60 to the controlled switch, voltage sensing line 62a to sense the voltage, $V_{reference}$ across the solenoid and voltage sensing line 62b to sense the battery voltage, V_{bat}.

In operation of the embodiment of figure 4, controller 146 switches the solenoid off for a brief period of time by sending a control signal to PWM 42, then the controller switches in the reference resistor by sending a control signal to controlled switch 56 resulting in the closing of switch 56. The controller may then sense $V_{reference}$ and estimate the coil resistance, R_{new} as:

$$R_{new} = R_{reference} * V_{reference} / (V_{bat} - V_{reference})$$

Once R_{new} is known, a corrected average voltage may be determined utilising expressions 1 and 2 set forth hereinbefore.

In this embodiment, the solenoid must be switched off for a sufficiently long time to allow transients to pass.

In another embodiment, the controller first switches the solenoid off then applies a current source onto the solenoid coil. The controller measures the voltage across the coil and then estimates the actual coil resistance using Ohm's law. With the coil resistance known, expression 1 and 2 set forth above are utilised to obtain a corrected average voltage which may be applied to the solenoid.

Although this embodiment uses a testing current source, the output of the testing current source may be magnitudes smaller than the requisite output of a current source which is used to precisely control a solenoid valve. Therefore, the testing current source is much less expensive and smaller than a current source used to control a solenoid valve.

To further enhance the accuracy of the control of the solenoid valve, the controller may be modified to also measure the voltage output by the voltage source. If this voltage is not at its nominal value, the controller may adjust the average voltage to compensate.

Other modifications will be apparent to those skilled in the art and, therefore, the invention is defined in the claims.

The embodiments of the invention in which an exclusive property or privilege is claimed are defined as follows:

1. A method of controlling a solenoid valve comprising the steps of:

applying a control voltage to said valve;

measuring resistance of a solenoid coil of said solenoid valve;

adjusting said control voltage based on said measured resistance.

2. The method of claim 1 wherein said step of measuring resistance comprises measuring temperature of said solenoid coil and determining resistance based on said measured temperature.

3. The method of claim 2 wherein said solenoid valve controls hydraulic fluid flowing to an hydraulic cylinder and wherein said step of measuring temperature comprises measuring a temperature of hydraulic fluid flowing through said valve.

4. The method of claim 2 wherein said solenoid valve is associated with a valve manifold and wherein said step of measuring temperature comprises measuring a temperature of said valve manifold.

5. A machine with a plurality of hydraulic cylinders, comprising:

a control valve associated with each of said hydraulic cylinders to control the flow of hydraulic fluid to each hydraulic cylinder;

an electrically operated solenoid to control a position of said control valve;

a voltage supply to provide a voltage across a coil of said solenoid;

a temperature sensor for measuring a temperature of said solenoid coil;

a compensator responsive to said temperature sensor for adjusting said voltage supply.

6. The machine of claim 5 wherein said temperature sensor is positioned in sensing relation with hydraulic fluid passing through said control valve.

7. The machine of claim 5 including a valve manifold for each said control valve and wherein said temperature sensor is in sensing relation with said manifold.

8. A driver for an electrically controlled solenoid valve, comprising:

a temperature sensor for measuring a temperature of a solenoid coil of said solenoid valve;

a compensator responsive to said temperature sensor for adjusting a voltage supply providing a voltage across said coil.

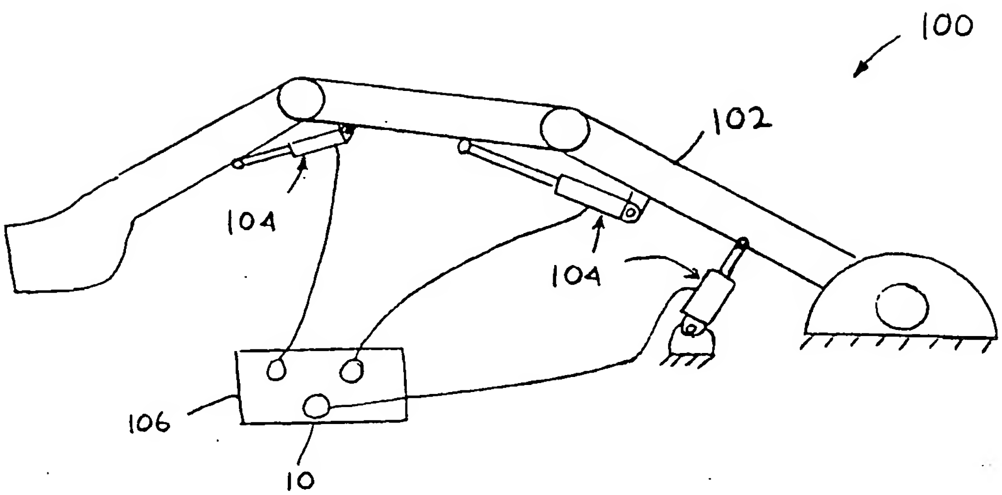


FIG. 1

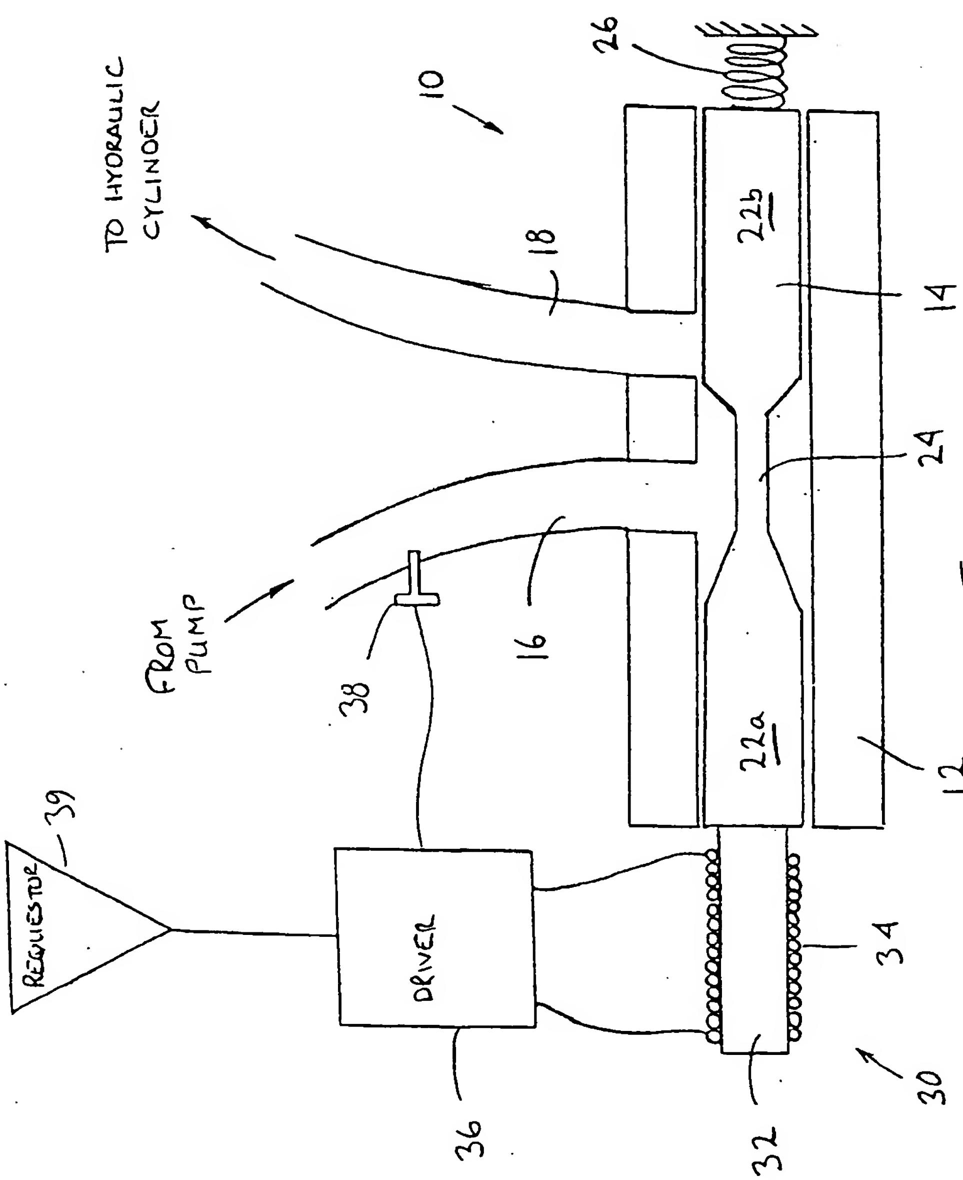

TO HYDRAULIC CYLINDER
FROM PUMP
REQUESTOR
DRIVER
10
12
14
16
18
22a
22b
24
26
30
32
34
36
38
39

FIG. 2

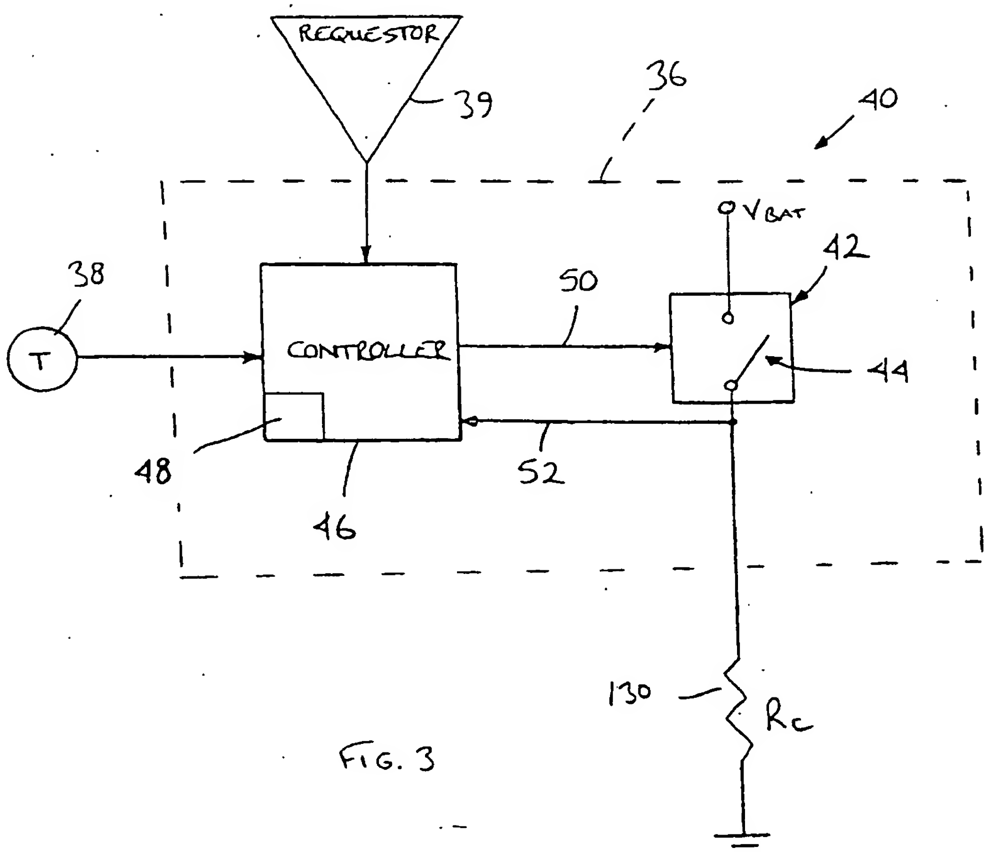


FIG. 3

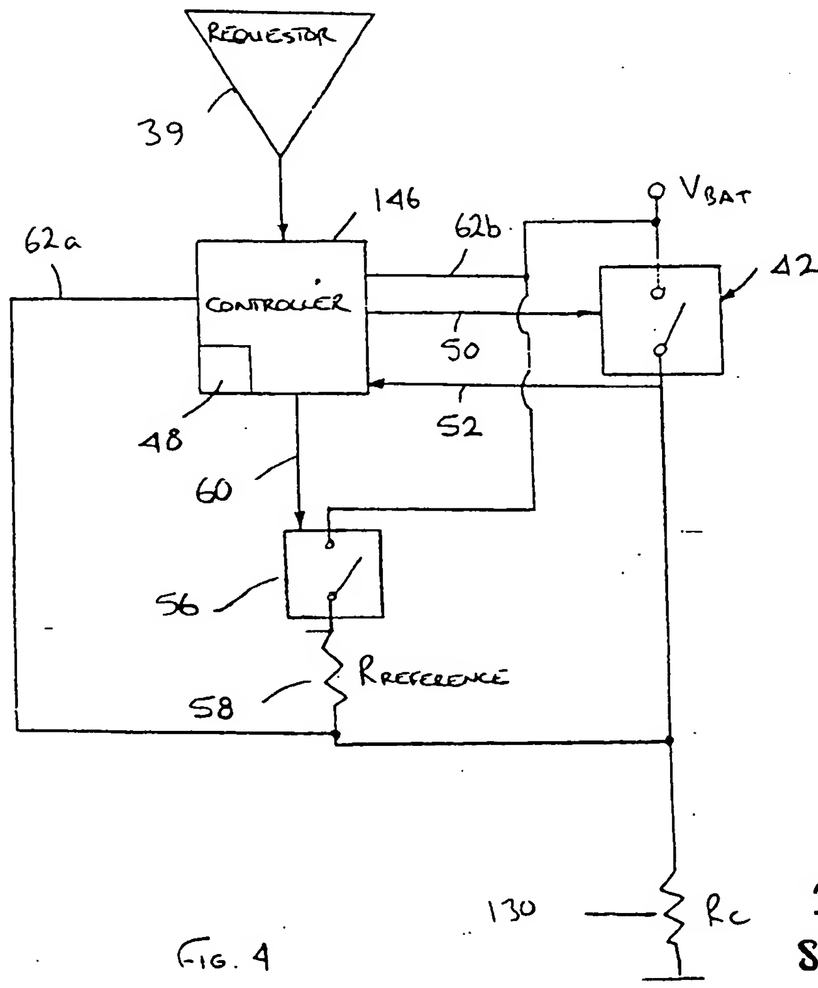


FIG. 4

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